

# PULSE LIKE GROUND MOTIONS – QUANTIFICATION ON DAMAGE SEVERITY

R.Sreekala<sup>1</sup>, K Muthumani<sup>1</sup>, A. Meher Prasad<sup>2</sup>, Nagesh R Iyer<sup>1</sup>

<sup>1</sup> CSIR-SERC, CSIR-Structural Engineering Research Centre, Taramani, Chennai, INDIA-600 113

<sup>2</sup> Indian Institute of Technology, Madras, Chennai, INDIA-600 113

E-mail of corresponding author: [kala@sercm.org](mailto:kala@sercm.org) or [kala@serc.res.in](mailto:kala@serc.res.in)

## ABSTRACT

Recent earthquakes around the world raise concerns about the quantification of damage potential of various strong earthquake ground motions. Earthquakes continue to result in vast loss of life and damage to property especially in populated urban areas like cities of Japan, China, Haiti etc. The maximum seismic energy observed in large velocity pulses is due to the forward directivity effects. The velocity pulse coupled with a large peak displacement during the pulse gives rise to considerable damage potential. The effects of these pulses on engineered structures are of concern and structural engineers need to provide design factors to the buildings. Quantitative definition of large velocity pulse has been carried out for a set of ground motion records. The selected ground motions were classified as pulse like and non-pulse like with an indicator characterizing it following the pulse extraction procedure. Pulse classification has been carried out as early or late arriving as they are of research and design interests. Period of the pulse is also identified as this is an important parameter for structural engineering decisions. The dataset used for the study included the recent earthquakes which occurred around the world. An analytical investigation on an equivalent SDOF system of a critical infrastructure has been carried out from a sample extracted pulse.

## INTRODUCTION

Earthquake engineering witnessed tremendous progress in recent years and it is an important consideration to determine the maximum physically possible ground motion. The strongest level of shaking expected at a site controls the maximum load the structure is subjected to. Ground motions which received particular attention in view of their effects on engineering applications are near source records. Near field earthquakes are known for their pulse characteristics due to directivity effects and are particularly damaging for structures. This type of ground motions with large velocity pulses combined with higher displacement demand requires engineering rethinking on the design aspects. Several studies have taken place around the world on ground motions having resonance or pulse-like nature, with concentrated energy at or near the pulse period.

Asymmetric high amplitude velocity and displacement pulses observed in fault normal nearfield earthquakes produce large residual displacements and normally push the structure into the non linear range. Rupture directivity and tectonic fling are the two conditions that lead to large long period pulses of ground motion. Directivity effects are the main causes of velocity pulses even though there are other causes which give rise to this phenomenon. They are site location, fault geometry and slip. If a site is located near an asperity in the fault rupture, the waves caused by that asperity can produce a pulse at the site. Detailed studies of the wave incoherence effect on the response of building structures were reported in Literature [1]. These studies indicate that the effect of kinematical interaction and the incoherence of waves always reduce the structural response, and this reduction may be substantial depending on the frequency content of the ground motion and the properties of the supporting soil. Forward directivity results when the fault rupture propagates toward the site at a velocity nearly equal to the propagation velocity of the shear waves and the direction of fault slip is aligned with the site. For both strike-slip and dip-slip faults, forward directivity typically occurs in the fault normal direction. Constructive interference of seismic waves passing through a complicated earth structure such as the edge of a geologic basin can also give rise to velocity pulses. A more detailed description of this phenomenon is given in literature [2]. Acceleration pulses can also occur at sites located at large distance from the epicenter due to path and local soil effects. Housner and Hudson [3] showed that the March 18, 1957 Port Hueneme earthquake consisted essentially of a single pulse. Since energy was contained in one pulse, the damage caused by this earthquake was unusual for a moderate earthquake. The paper discusses the various techniques for pulse identification and its application to engineering structures. Well known pulse like ground motion records and recent earthquakes in Newzealand and Japan have been used for the study with an analytical investigation on an equivalent SDOF system.

## REVIEW OF VARIOUS STUDIES ON PULSE LIKE GROUND MOTIONS

Starting from 1933, a large number of strong ground motions have been recorded in the world. To characterize the severity and the damage potential of the earthquake ground motion, various parameters and methods were identified and practiced during past two decades. These parameters can be grouped into any of the three main categories. They are classified as Peak Ground Motion values obtained from the digitized and corrected records, Spectral values obtained from the parametric integration of the equation of motion and the spectral values considering the energy balance equation of elastic and inelastic systems. Pulse type records are of interest to engineering community as they can induce high demands on structures and these huge demands may not be adequately captured by the current ground motion intensity measures such as first mode spectral acceleration. Even though there exists variety of methods and parameters to characterize the damage potential of strong earthquakes there exists a huge gap in identifying a real un-favorable ground motion indicator in the time or frequency domain which fits into the various classes of structures following the inelastic analysis.

The choice of selection can be simple thresholds on Peak Ground Acceleration (PGA) or Peak Ground Velocity (PGV) or complicated spectrum based criterion. The Arias Intensity ( $I_A$ ) proposed by Chilean engineer Arturo Arias in 1970 is a measure of the strength of a ground motion [4]. It determines the intensity of shaking by measuring the acceleration of transient seismic waves. It has been found to be a fairly reliable parameter to describe earthquake shaking. It is defined as the time-integral of the square of the ground acceleration which is an intensity measure. Significant-duration parameters are defined as the time interval across which a specified amount of energy is dissipated. The duration of shaking is directly related to the inelastic deformation and energy dissipation demands on the structure. If a structure is deformed beyond its elastic limit, the amount of permanent deformation will depend on how long the shaking is sustained. Therefore, the duration of earthquake shaking is a very important measure of the damage potential of the ground motion. The duration of strong ground motion can vary depending on the magnitude, source distance, and local site conditions. The duration of strong ground motion increases with increasing earthquake magnitude. Significant duration from the Arias integral has been widely used in recent engineering practice.

Apart from this there exists other methods based on wavelet analysis, methods based on entropy principle to identify resonant accelerograms [5] and Significant Peak Ground Acceleration –SPGA [6] which are described in detail in the paper. Other methods determining the most un favourable real seismic design ground motions are proposed by Zhai et al., [7], which is based on the critical excitation method by Denrick, 1973.

## NUMERICAL INVESTIGATION ON MEASURES OF SEVERITY OF GROUND MOTIONS

### Peak Values of measured signals and computed wave forms

An ensemble of strong motion earthquakes were taken for this study and the strong motion parameters were calculated. Table 1.gives some of the parameters in characterizing the damage potential of some of the well known strong ground motions. These parameters range from a simple instrumental peak value to values obtained through mathematical derivations based on the work by Kramer et al, 1996 [8]. Here for the earthquakes listed in Table 1, the characteristics were computed.

### Pulse Identification using Wavelet Analysis

For non stationary signals such as earthquake ground motions, it can be advantageous to represent the signal as a summation of wavelets rather than a summation of stationary sine waves. Baker, 2005classifies ground motions based on wavelet analysis and the procedure is followed in Next Generation Attenuation project (NGA) [9]. The approach uses the wavelet transform to extract pulse like signals from a ground-motion time history and then classifies the ground motion by comparing the original ground motion with the residual ground motion after the pulse has been extracted. To evaluate a ground motion, first the continuous wavelet transform of the velocity time history is computed, and the coefficient with the largest absolute value is identified and the Daubechies wavelet of order four is used as the mother wavelet. The wavelet associated with this coefficient identifies the period and location of the pulse. Here the wavelet coefficient is equal to the energy of the associated wavelet, so the selected pulse is also the one with the largest energy. This wavelet is subtracted from the ground motion, and the continuous wavelet transform is computed for the residual ground motion. Here an attempt is made to study the pulse characteristics of recent earthquakes which happened in Newzealand and in Japan (brief description is given later in the text) and is compared with Pacoima earthquake. MATLAB- mathworks software is used for the study. Table 2 gives the identified parameters for the classification of pulse like records.

Table 1:- Computed parameters for the characterization of the various strong motions

Earthquake rec.(Accln Time Histories)	Kobe	Chi-Chi	Coraltos	Emeryville	Imperial valley	Kocaeli	Loma Prieta	Northridge	Sakari	Trinidad
Max. Accln	0.35	0.36	0.80	0.25	0.31	0.35	0.37	0.57	0.63	0.16
Max Vel.	27.65	142.51	58.73	43.38	29.66	124.96	65.94	26.01	77.37	18.13
Max Displ	9.12	257.35	64.34	9.29	13.08	225.03	29.90	2.24	59.11	14.33
$V_{max}/A_{max}$	0.08	0.40	0.08	0.18	0.10	0.37	0.18	0.05	0.13	0.11
Accln,rms,	0.07	0.08	0.13	0.05	0.05	0.06	0.06	0.09	0.12	0.03
Vel.RMS	7.97	38.04	15.30	10.23	6.31	42.58	12.07	4.60	18.89	5.23
Displ.,RMS	3.03	119.25	34.58	4.78	3.70	80.05	8.80	0.78	38.64	5.54
Arias Intensity	1.67	4.49	4.14	0.90	1.70	2.59	2.38	1.39	4.75	0.71
Specific Energy Density	1575	72345	3955	2146	1594	81640	6891	260	7133	1201
Cum. Abs. Velocity	1050	2505	1342	681	1311	1812	1495	606	1584	975
Acc.Spect Intensity	0.33	0.19	0.45	0.18	0.28	0.17	0.27	0.42	0.55	0.11
Vel.Spect. Intensity	154	402	247	192	133	216	251	98	267	88
Charact. Intensity	0.08	0.15	0.18	0.06	0.08	0.10	0.09	0.09	0.20	0.04
Predominant Period	0.16	1.54	0.56	0.00	0.46	0.00	0.78	0.16	0.16	0.00
Sustained MaxAccln	0.27	0.27	0.43	0.24	0.25	0.18	0.27	0.41	0.47	0.11
Sustained Max.Vel.	23.76	132.21	46.22	31.26	28.09	81.69	40.77	16.32	50.31	17.14
Effect. Design Accln	0.33	0.36	0.65	0.24	0.30	0.34	0.36	0.54	0.53	0.16
Significant Duration	10.93	28.96	7.27	8.80	24.10	25.73	21.71	4.47	8.71	24.34

Note :- the units for acceleration in “g”, velocity in “cm/sec” and displacement in “cm”.

If pulses like ground motions caused by directivity effects are of primary concern, two additional criteria are proposed to exclude ground motions with pulses arriving late in the record and low-intensity ground motions with simple time histories that coincidentally appear to be pulse like. The procedure is based purely on signal-processing techniques; the ground motion’s source–site geometry is not used when making a classification. Compared to discrete wavelet transform, continuous transform has more advantages as its higher resolution is useful for precisely identifying the largest coefficient, which will indicate the period and location of the near fault pulse. In this procedure ground motions with PGV values less than 30cm/sec (threshold value) have been excluded as they are mostly low amplitude records without directivity effects.

Table 2:- Pulse identification using wave let analysis on typical Ground motions

Parameter s	Remarks	New zealand Earthquake (Feb.2011,Christ Church)	Pacoima Earthquake(Feb 09 1971)- Rotated clockwise by an angle of 31.0-FN azimuth 195	Japan Earthquake (11 Mar 2011)	Pacoima Earthquake (Feb 09 1971)- Comp. S16 E
Pulse Indicator	Range 0 - 1. > 0.85 -pulse like <0.15 - non pulses..	0.57	0.97	0.00185	0.79
Late	1 if $t_{20\%,orig} * FN < t_{10\%,pulse}$	0	0	1	0
PGV (cm/sec)	PGV (*FN) >30 cm/s pulse-like.	84.80	116.48	271.50	114.92
Is Pulse	1 - pulse-like 0- non-pulse-like.	0	1	0	0
Tp (s)	Psuedo-period of the pulse.	1.51	1.60	5.74	1.62

\*FN denotes Fault Normal component

The parameter late mentioned in Table 2, row no: 3 is an Indicator of late-arriving pulses. Ground motions with directivity effects exclude late arriving pulses although it is of research interest. "True" values indicate that the  $t_{20\%,orig}$  value of the fault normal component is less than  $t_{10\%,pulse}$  and is denoted by value 1 or else 0. Tp is the psuedo-period of the extracted pulse. This is provided for all ground motions (i.e., even for ground motions where this extracted pulse was determined to not be significant).

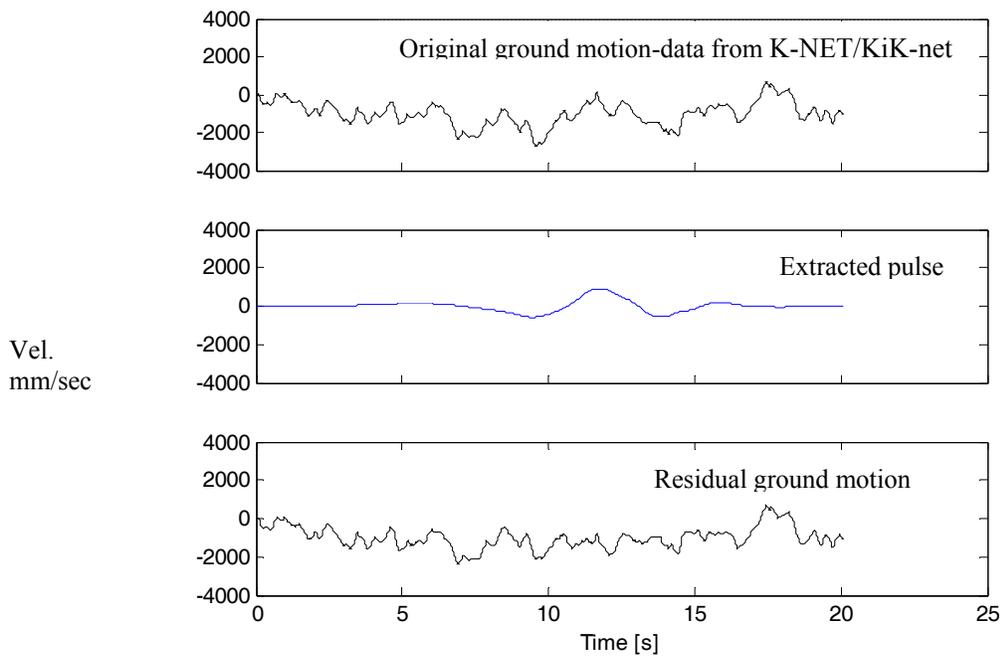


Fig. 1: Japan Earthquake - 11 March 2011 – Pulse extraction

On March 11<sup>th</sup> 2011, a massive scale earthquake of magnitude 9.0 occurred in Japan with low angle reverse fault focal mechanism. An attempt has been made to process the data available through the strong motion network K-NET/KiK-net using wavelet analysis. The results are tabulated in Table 2. The original ground motion for the few seconds, extracted pulse and the residual ground motion are given in the Fig 1. Here it is observed that the Japan earthquake is not classified as a pulse and late arriving waves are found to be present. The value of  $T_p$  is also significant as we are aware that Japan earthquake belong to one of the low frequency events-LFEs-observed in ocean sub-duction zones. The wavelet analysis clearly categorizes this as non pulse like behaviour and predicts the severity accurately. Similarly Christchurch earthquake in New-zealand (February 2011) was also subjected for the study. The pulse extraction procedure was repeated using MATLAB program and the characteristic of the wave form are shown in Table 2.

During the past 15 years an ever-increasing database of recorded earthquakes has indicated that the dynamic characteristics of the ground motion can vary significantly between recording stations that are located in the same general area. The first recorded data in the United States that contained damaging acceleration pulses was the record obtained at Pacoima Dam during the San Fernando, California earthquake of February 1971. The pulse direction normally indicates the compass heading in which the largest peak velocity is acting. If this direction corresponds to either fault normal or fault parallel direction, it is indicated by FN or FP respectively. Otherwise (if the principal direction does not correspond to either the fault normal or fault parallel direction), the direction is indicated as an azimuth angle in degrees. Hence the accelerograms which are rotated towards the fault normal direction shows clear pulse like characteristics as evident from the values given in Table 2, column 4 and the plots are shown below in fig.2. The spectral velocity plots gives the value of  $T_p$  as 1.1 seconds and wavelet analysis gives 1.6 seconds and hence the pulse component in the rotational accelerogram is very clear from the wavelet analysis.

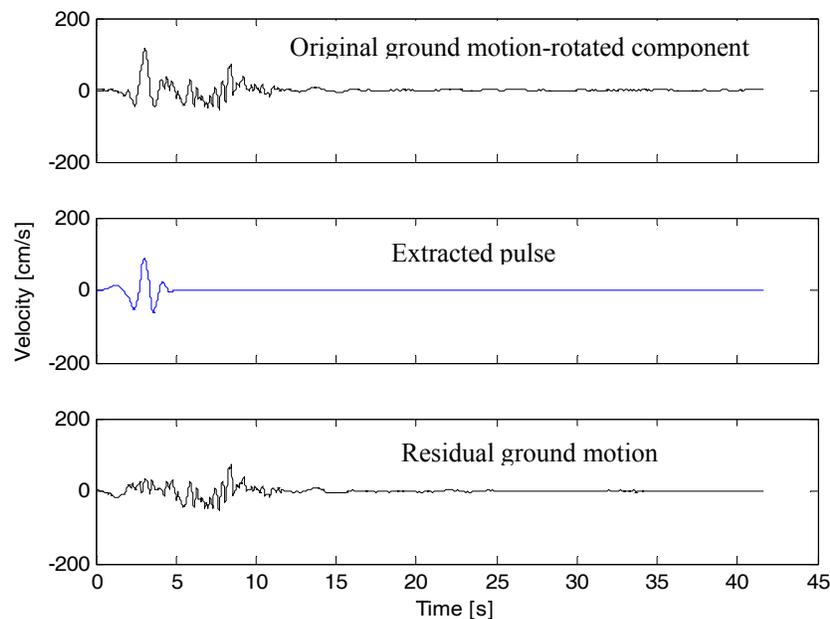
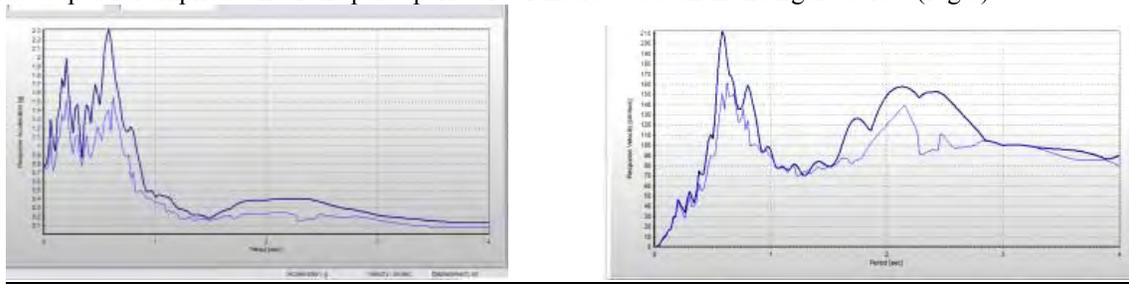


Fig. 2: Pacoima dam rotated component – Pulse extraction

### Spectral Identification

The ground motions recorded in Chi-Chi earthquake has some unique characteristics (such as, near-fault velocity pulse and long duration ground motions) in comparison with other ground motions. On September 21, 1999, an earthquake of magnitude 7.7 took place in the central part of Taiwan. The epicenter of the earthquake was located at 120.82 E and 23.85 N near the town of Chi-Chi and the focal depth was 8.0 km. A surface rupture along Chelungpu fault with a length of about 105 km was observed, for which the largest measured vertical offset reached more than 9 m. Ground and geophysical surveys also showed that the shock resulted from reactivation of the Chelungpu fault. The rupture was generated by the combination of reverse, strike-slip and normal movements, particularly in the northern part of the fault, thus far more complicated than that of a simple fault. The spectral

acceleration and velocity plots for Chi-Chi earthquake is done in the user friendly software are as shown below. The increased spectral amplitude near the pulse period is of interest as seen in the figure below (Fig.3).



(a) Acceleration Spectra

(b) Velocity Spectra

- Bold line indicates elastic spectrum and the thin line indicates constant ductility inelastic spectrum,  $\mu = 1.5$   
Fig.3. Spectral plots for Chi-Chi Earthquake (a) Acceleration spectra (b) Velocity Spectra

Response spectra representation can either be elastic or inelastic; whereas inelastic spectra can either be constant strength or constant ductility. Constant ductility spectra are useful for the preliminary design of structures where the global displacement ductility is known. Through the yielding coefficient, the required lateral strength can be evaluated from the elastic lateral strength.

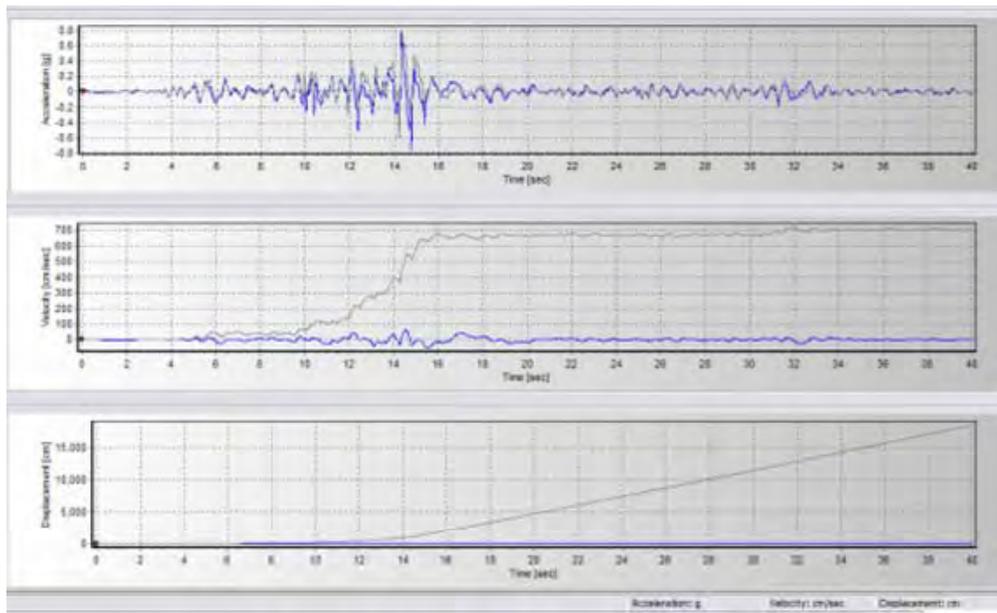
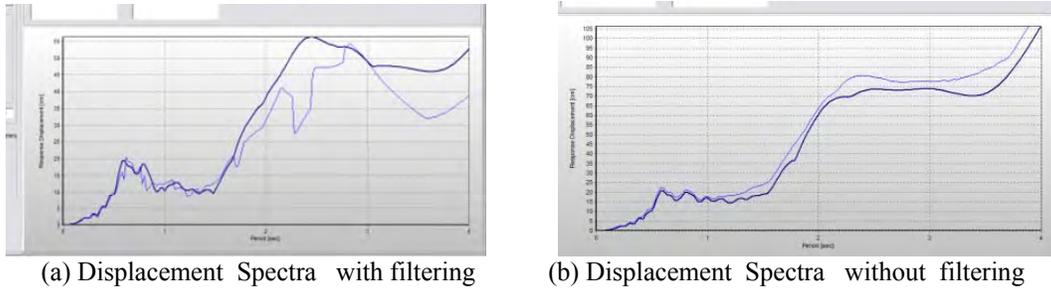


Fig.4: Chi-Chi Earthquake Acceleration, Velocity and Displacement time histories - Blue line indicates data after correction, Grey line without correction- Huge variation in velocity (Almost 6 times) and displacement

The spectral diagram of the ground motion with and without data processing makes an interesting reading. It is found that the spectral displacements are greatly affected by the data correction procedure and not the spectral acceleration or velocity. Fig.4 gives the acceleration, velocity and displacement time histories with and without correction. For correcting the acceleration wave forms, linear baseline correction and butter worth band pass filter (low cut = 0.1 hz, high cut = 25Hz, order 4) is used. Without correction, the spectral displacement demands are huge (105 cm instead of 55cm with correction) as seen in Fig.5.. In the generation of spectra, the numerical integration parameters are set as  $\beta = 0.25$ ,  $\gamma = 0.50$ , Maximum  $dt/T = 0.02$ , Tolerance = 0.000001.

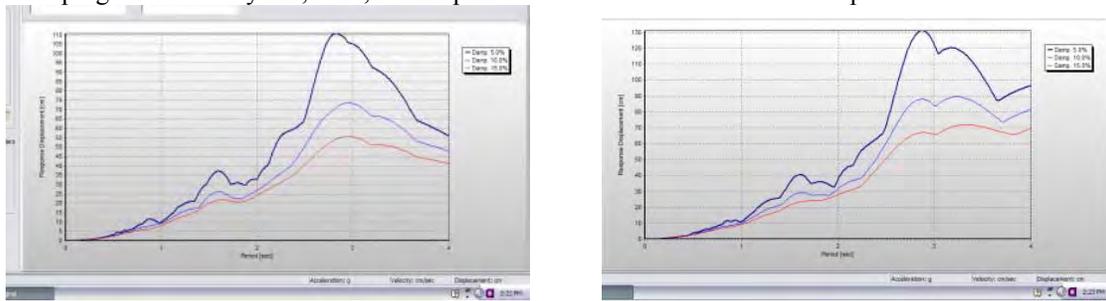


(a) Displacement Spectra with filtering (b) Displacement Spectra without filtering

- Bold line indicates elastic spectrum and the thin line indicates constant ductility inelastic spectrum with  $\mu = 1.5$

Fig.5: Displacement Spectral plots for Chi-Chi Earthquake (a) with filtering (b) without Correction /filtering

A similar process for Kocaeli (Turkey 1999, Mw 7.4) earthquake gives rise to minor deviations in the spectral displacement as shown below (15% difference in value). The graph below shows the spectral displacement for three damping ratios namely 5%, 10%, 15%. Spectrum correction methods are as explained earlier.



Corrected record-Spectral –displ. plots (a) with filtering (b) without correction/filtering

Fig. 6. Displacement Spectral plots for Kocaeli Earthquake (a) with filtering (b) without correction/filtering

### Resonant Accelerograms

Resonant ground motions are characterized by its energy contained in a narrow frequency band[5]. Here measures were identified based on the frequency content of the ground motion using the entropy principle and the dispersion index without doing non linear analysis of the structure. They are based on the geometric properties of the power spectral density function of the ground acceleration. The fig. 7 below give the power spectral density(normalized) for three near field earthquakes, namely Chi Chi, Kobe and Kocaeli all are of nearly same maximum acceleration level. But the spectra clearly identifies resonant accelerograms or each of them belong to Kanai Tajimi model, band limited or narrow band respectively. The spectral density is shown in the y-axis and time in seconds is indicated in x-axis.

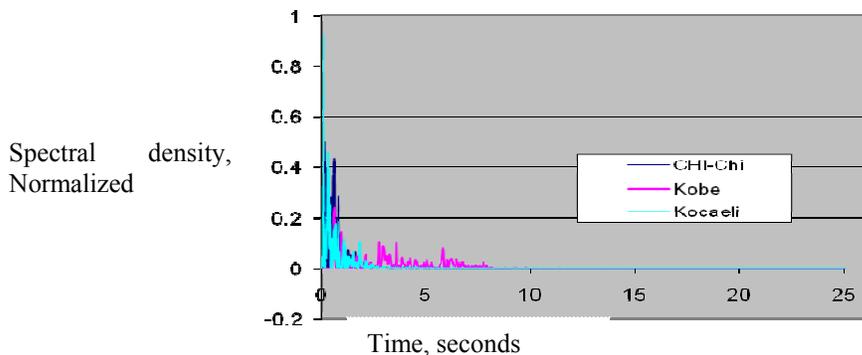


Fig. 7: Spectral density plots

### Significant Peak Ground Acceleration (SPGA)

An equivalent rectangular acceleration pulse, called the significant peak ground acceleration ‘SPGA’ is identified as the measure of ground motion severity in recent years[6]. Compared to other available measures, the

SPGA correlates significantly better with the inelastic response of structures having periods of less than about 1 s and displacement ductility of at least two. Inspecting the response of the inelastic SDOF system and relating the response to the corresponding acceleration pulse of the Kobe-Takatori ground motion, it becomes clear that the maximum displacement response of the system is mainly due to the acceleration pulse. This new measure not only takes the variation of the ground velocity, but also the duration over which such variation occurs.

**REPRESENTATIVE PULSE FOR EXPERIMENTAL TESTING & ANALYTICAL INVESTIGATION ON AN SDOF SYSTEM**

A single large representative velocity pulse has been identified during the studies in the Pacific Earthquake Engineering Research Centre, 2002 (PEER)[9]. It has been identified that the average number of cycles of a near fault pulse varies from 0.5 to 2 cycles and most of the cases it is 1. A study is made here by applying single representative pulse of 3seconds duration to a Single Degree of freedom model (SDOF). The model has a cyclic frequency of 0.92 Hz with structural yield strength of 1200kN. The input yield displacement is 5cm and assumed damping is 5% critical. The post yield stiffness ratio is kept as 4%.

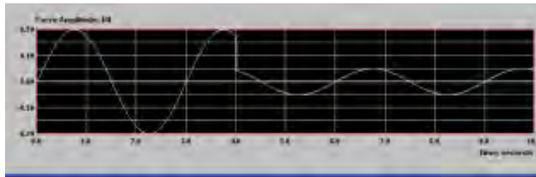


Fig. 8: Applied pulse (3 s-pulse period)

The forcing function is the ground acceleration of 0.2g where two sinusoidal waves of 0.15 and 0.05 amplitude was superposed in phase for a duration of 4 seconds and 10 seconds respectively. A non linear analysis was carried out and the computed displacement response was 22cm with 4 yield reversals.

Spring force realized  
 Displacement Computed – Maximum 22cm  
 No: of yield excursions: - 04

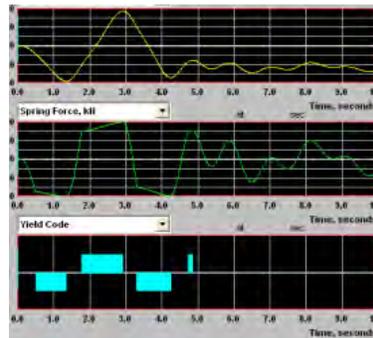


Fig. 9: Computed response for the applied pulse

When the same structure was analysed for free vibration for 10 second duration for a given initial wave velocity of 80 cm/sec., the acceleration shoots up to 0.4g for the computed displacement of 14cm. The same model subjected to a free vibration with initial displacement of 22cm, give rise to a computed velocity of 74cm/sec with 0.28g acceleration. This observation is of importance while doing laboratory testing using shaking tables. Higher velocities bring in higher accelerations even during free vibration with smooth sinusoidal time history. Hence pulse type excitations require padding with zeroes at the beginning as well as the end of the pulse for realizing the actual response considering enough actuator safety provision. Also it is of importance to maintain a threshold value of pulse parameter, displacement, velocity or acceleration even in the case of free vibration depending on the structural time period.

**ISSUES TO BE SOLVED**

Structural response characteristics are also of importance towards quantification of damage potential. It is to be kept in mind that the ground motion alone or elastic quantities derived from it cannot characterize the damage potential of earthquakes. Identification of a real un-favorable ground motion indicator in the time or frequency domain which fits into the various class of structures following the inelastic analysis need to be brought in for the robust seismic resistance methodology. The identification of real pulse type ground motion requires lot of skillful engineering judgment. Some basic issues of the collected signals or signals used for the experimental research need

to be addressed. The values of PGV reported for a single record may vary significantly depending on the 1) processing adopted for the data correction [there are chances that conventional filtering adopted filters out long period data] 2) use of components as such without specifying directional features (e.g.; - horizontal components have been rotated or not as evident in Table 2 for the case of Pacoima). Also near source ground motions demand large drifts for a wide range of periods. This underscores the importance of displacement based design procedures in the short period region. In the short period region, effective damping concept for modifying the elastic response will not provide reliable estimates for determining the higher displacement demands in strong near field motion with forward directivity effects. The spectral displacements are underestimated in ATC 40[10] based procedure. For buildings equipped with dampers this becomes a serious issue. Alternative methods to modify the response need to be sought for than the existing capacity based procedures. Instead of using band pass filters, a method can be tried to use the raw velocity data as such with continuous or segmental curves added to it on either side. This procedure assures that the ground motion starts and ends with zero velocity.

## CONCLUSIONS

Earthquake resistant design of critical infrastructural facilities requires proper quantification of the maximum level of ground motions it is subjected to. One of the most important decisions in carrying out proper design is to select a design earthquake that adequately represents the ground motion expected at a particular site that would drive the structure to its critical response. The severity or damage potential has been interpreted in various ways by the research community. Although pulse like ground motions is known for many years, the extraction of the pulse and their application is limited. In the laboratory level, identification of a suitable time history representing the pulse characteristics is of importance. The pulse like ground motions give rise to unexpected elastic and inelastic seismic displacement demands and their non standard spectral shape in a range around the pulse period is of interest. Some recent tools to investigate the pulse like records are applied in the paper using well known pulse like ground motion records and recent earthquakes in Newzealand and Japan. Even though various methods tried in the paper throws light on the comparative merits of each method, it also shows lot more improvement need to be brought into for a robust methodology. More research efforts are needed towards quantification of damage severity of pulse like ground motions through experimental and analytical investigations.

## ACKNOWLEDGEMENT

The paper is published with the kind approval of Director, SERC and his constant encouragement and advice is gratefully acknowledged. The authors gratefully acknowledge their colleagues in ASTaR laboratory for the kind support and encouragement.

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